THE CHARACTERISTICS OF THE EPPLEY PYRHELIOMETER

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The Eppley pyrheliometer is so widely used for the measurement of the intensity of total solar and sky radiation on a horizontal surface that a knowledge of its limitations should be of interest. In connection with the Cabot Solar Energy Utilization Program at Massachusetts Institute of Technology, it has been necessary to obtain an accurate continuous record of solar radiant energy; and an Eppley instrument has been used, the characteristics of which have been studied in considerable detail to assure maximum accuracy. It is the purpose of this article to present some of the results of that study as a guide to others interested in minimizing errors of measurement.

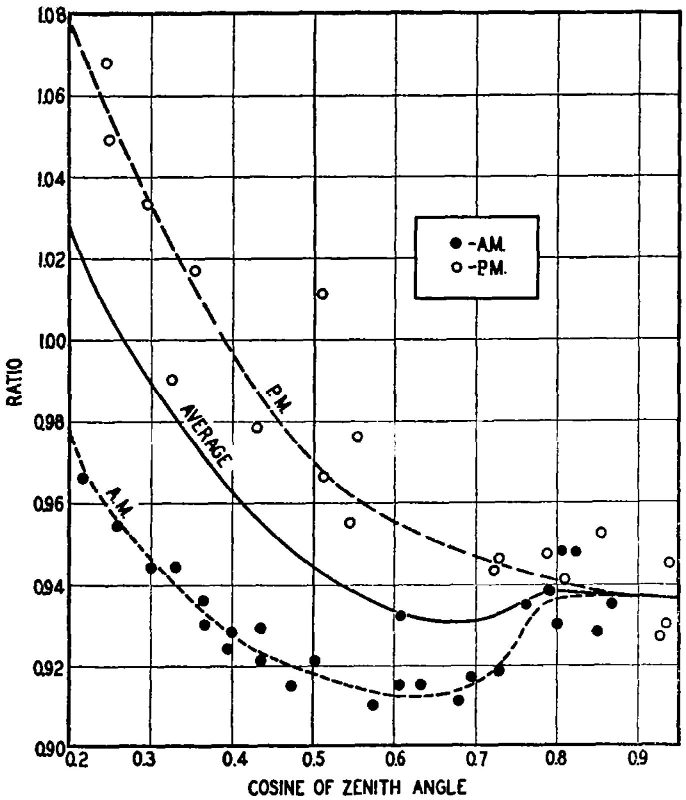

FIGURE 1.—Calibration of Eppley pyrheliometer No. 434: the relation of zenith angle to ratio of calories per sq. cm. per millivolt, as determined by Smithsonian silver disk pyrheliometer, to corresponding constant factor furnished with instrument. Date of experiments, June 7 to July 3, 1940.

In connection with a study of the performance of flat-plate solar energy collectors, where an hour-by-hour comparison of performance was made with that calculated from the pyrheliometric record, it became apparent that there were large unexplained differences between the calculated and the experimental performance of the collectors. Other sources of error having been studied and minimized, the pyrheliometer itself (No. 434) was suspected. Accordingly, a standard Smithsonian silver disk pyrheliometer was borrowed from the Weather Bureau and used to recalibrate the Eppley instrument. The results appear in fig. 1, where the cosine of the zenith angle of the sun is plotted against the ratio of the calories per sq. cm. per minute required to generate one millivolt to the corresponding quantity previously reported for the instrument. The data spread considerably, due in part to fluctuations in solar intensity which make reproducibility difficult; but the plot leaves little doubt of the need for a revision of the instrument constant and for the use of an instrument constant which is a function of zenith angle in order to obtain accurate data. Although normal precautions had been taken to mount the instrument in a horizontal position by sighting over a long spirit level, fig. 1 gives evidence of an effect of time of day (whether morning or afternoon), which might be due either to variations in the bulb glass or to lack of horizontality of the receiver disk. To determine more definitely whether the cosine of the angle of incidence of the solar beam on the instrument was the sole factor in obtaining the instrumental constant, a new experiment was undertaken.

A 1,000-watt projection bulb was mounted on a framework, which was in turn mounted equatorially with the pyrheliometer at its center. By this means the projection-bulb could be made to imitate in detail the sun's position at any time of day or year. A series of readings of the Eppley instrument was obtained, with elimination of the small effect of fluctuating voltage on the brightness of the projection-bulb by taking every other reading with the bulb in a certain standard overhead position and expressing all other readings as a ratio to the reading in the standard position. The data obtained were plotted as response of the instrument versus time of day for each of several "declinations" of the "sun." The resulting curves were smooth enough to indicate no particularly bad spots in the pyrheliometer bulb, but asymmetrical to an extent which could be explained by assuming that the pyrheliometer surface was about 1.5° off horizontal, an amount which cannot be detected by the eye because of the small size of the surface and the fact that its plane does not coincide with the plane of the top of the shell in which it is mounted. Making this correction and dividing all the responses by the cosine of the zenith angle, one obtains the relative response of the instrument per unit of intercepted energy. When the reciprocal of this value, proportional to calories per sq. cm. per min. per millivolt, is plotted against the cosine of the zenith angle, figure 2 is obtained. (The absolute height of the curve was established by making the average of all points corresponding to cosine of zenith angle greater than 0.6 equal to the average in the corresponding region of figure 1; for some reason, probably a small error in "declination" of the "sun," the points for $-9.75°$ declination were decidedly too high, as can be seen in figure 2, and they were therefore ignored when the solid curve was drawn through the points.) Figure 2 is in reality a measure of the reproducibility of an Eppley instrument, inasmuch as the deviations cannot be explained by any error in potentiometry or fluctuations in intensity of source. The deviations of 1 percent or so (in the flat part of the curve) from the smooth solid curve are most probably due to local imperfections in the bulb and represent deviations for which it is impractical to allow in using the instrument. The absolute shape of the solid curve in figure 2 may differ somewhat from a similar curve obtained using sunlight itself, inasmuch as the change in absorptivity of a black surface, which undoubtedly accounts for the curvature, may be somewhat different for solar radiation and for the longer wave-length radiation from a 1,000-watt bulb.

The experience with the 1,000-watt bulb emphasized the need for an alignment technique better than that obtainable by visual observations of the pyrheliometer, since the data of figure 2 would have been much more widely spread if the instrument had not been corrected for the

*At various times H. E. Miller and Mrs. H. F. Cullinane assisted in obtaining data.

small tilt. Accordingly, two spirit levels were affixed (at right angles to each other) to the base of the instrument, which was then leveled by the following technique: a piece of plate glass was leveled to an accuracy of about 0.1° with a good quality spirit level. The Eppley instrument was then placed on the glass, and the 1,000-watt bulb was mounted 18 inches away at an altitude of about 10° above the horizon of the pyrheliometer. The instrument was then rotated about its center while readings of its response were taken. (Care must be exercised not to let the center of the disk move laterally more than one-eighth inch during the rotation to prevent an error of 1 percent in the readings.) By trial and error the pyrheliometer was leveled until this process of rotation produced a minimum

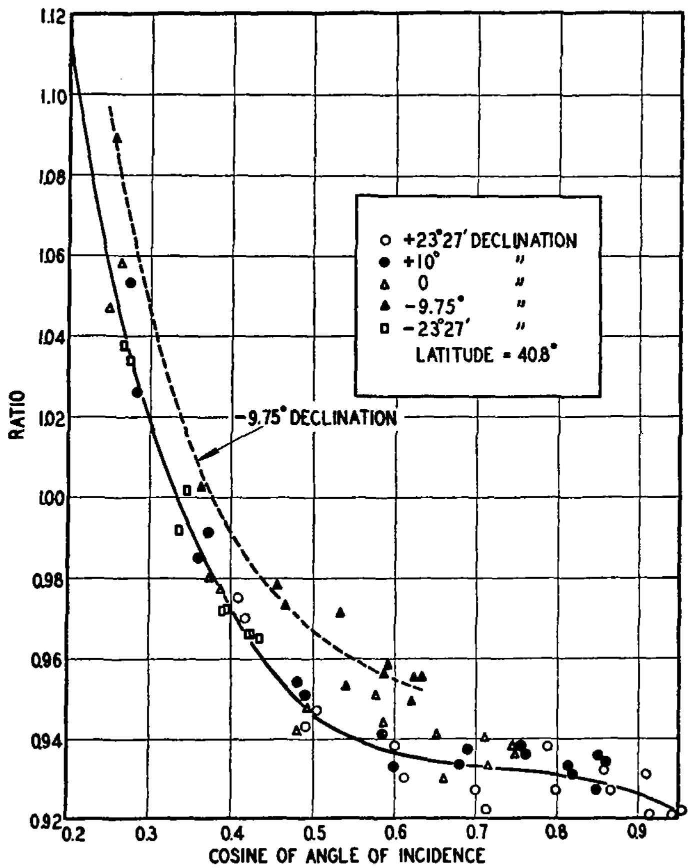

FIGURE 2.—Ratio of true calories per sq. cm. per millivolt (as a function of angle of incidence) to the calibration constant furnished with pyrheliometer. Data obtained using a 1,000-watt projection bulb equatorially mounted in order to imitate sun's apparent motion.

change in the readings. Preferably the same technique is repeated with the lamp at a new, somewhat higher, altitude. The position of the levels was then finally fixed so that the horizontality of the receiving surfaces of the instrument could be reproduced when the pyrheliometer was moved to its position on the roof of the solar energy building at the Massachusetts Institute of Technology.

Some months later, as a preliminary to the recalibration, by the Weather Bureau staff, of the Eppley pyrheliometers in use at the various solar radiation measuring stations in the United States, an Eppley instrument No. 197, carefully calibrated by the Weather Bureau staff using a Smithsonian silver disk as a standard, was set up beside the instrument No. 434 studied above, normal precautions being taken to put instrument No. 197 into horizontal position without resorting to the special technique previously described. Intercalibrated potentiometers of good precision were used to obtain simultaneous readings of these two pyrheliometers throughout one day and part of another. The results, plotted as relative response of the instruments versus solar time, indicated a variation of 4 percent throughout the day (9 a. m.–3 p. m. in February). The trend of the curve indicated the possibility that the second instrument had not been perfectly level. To test this possibility, spirit levels were affixed to the base of the second pyrheliometer and then adjusted until they were level, without moving the instrument. Then, during a clear day, the readings of this second instrument were compared with those of the original pyrheliometer, No. 434, rotating the second instrument 180° every reading and using the levels to insure that the instrument tilt was not changed except for orientation during each half revolution. The results appear in fig. 3 as two curv'sə indicating plainly that instrument No. 197 when in position 1 was tilted slightly toward the East. By taking relative readings at 8:30 a. m. and 3:30 p. m., it is possible, by the use of equations giving the angle of incidence of the sun's rays on a tilted surface,

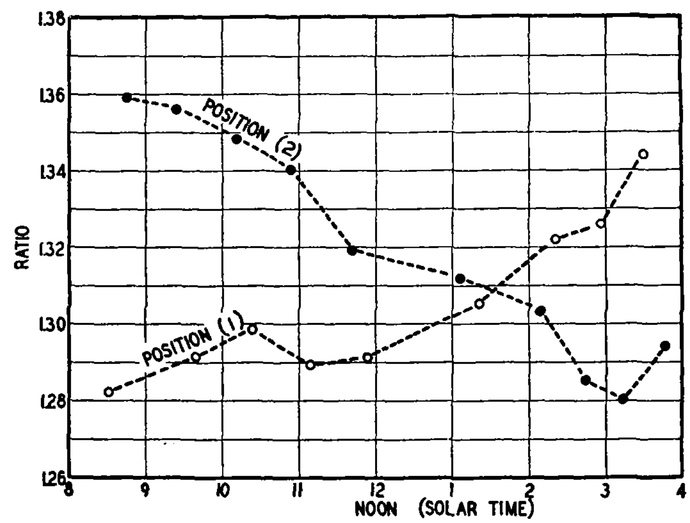

FIGURE 3.—Ratio of millivolts generated by pyrheliometer No. 434 to that by No. 197. No. 197 (position 2) is rotated 180° from the original position 1. Ordinary technique was used in levelling instrument No. 197. Date of test, February 26 and 27, 1941.

to calculate the amount and orientation of the tilt. Such calculations indicated that instrument No. 197 was tilted 0.65° in a direction about 20° South of East, when in position 1. The instrument was then removed to the laboratory, its tilt changed by the amount previously calculated, and the levels readjusted to read level. It was then remounted on the roof for a second test against instrument No. 434. Figure 4 shows the results of this test and indicates the considerable improvement due to releveling. The point coordinates, and departure from the mean of all points, appear in table 1, together with the average percentage departure from the mean, 0.58 percent.

Inasmuch as it was impossible to detect by visual observation the small tilt of the instrument in the original comparison with instrument No. 434, the importance of some such technique of leveling as that described above is obvious. Figs. 3 and 4 indicate that Eppley instruments mounted in the conventional way may be in error as much as 3.6 percent in the region of zenith angle of the sun less than 70°, provided the correct instrument constant (for a level instrument) is known, and assuming that the original tilt of instrument No. 197 may be considered to be the maximum probable.

Figures 2 and 4 lead to the conclusion that any single reading of an Eppley instrument, even though carefully calibrated, may be in error by 1 percent or possibly more, especially for large zenith angles of the sun. The average of a large number of readings at different times of day and year can, however, be very much more accurate as indicated by the following comparison: The mean response of the first instrument studied, No. 434, was established by the Smithsonian silver disk pyrheliometer as 9.10 millivolts per cal. per sq. cm. per min. in the range of cosine zenith angle 0.6 to 0.95 (zenith angle, 53.1 to 18.2°). The response of the same instrument determined by the transfer of calibration from the carefully standardized pyrheliometer No. 197 is $1.312 \times 6.88 = 9.03$ millivolts per cal. per sq. cm. per min., in the same range of zenith angle. These two values were obtained entirely independently and differ by only two-thirds of 1 percent.

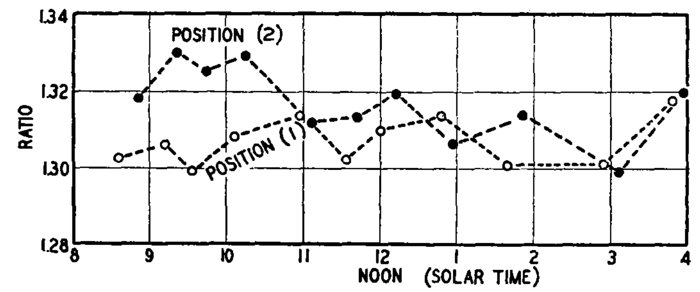

FIGURE 4.—Ratio of millivolts, pyrheliometer No. 434, to millivolts, pyrheliometer No. 197, after No. 197 had been levelled by the special technique. Date of test, March 2, 1941.

The above shows the effect of horizontality, angle of incidence, and, to some extent, bulb imperfections on the response of the Eppley pyrheliometer. Close examination of the instrument reveals these other possible defects:

1. The black and white rings in the instrument are not all in the same plane. It is possible that they may be slightly curved.
2. The black surface, especially, appears to be coated to a varying thickness. In some spots, lumps of nondispersed pigment may be observed. These no doubt offer comparatively high resistance to heat transfer to the thermocouple junctions.

To these should be added the inevitable defect that the glass bulb does not transmit all the radiation falling on it. The zigzag nature of the curves in figures 3 and 4 suggests that orientation may have a small effect; therefore, the pyrheliometer should be oriented the same in use as during calibration. Otherwise a small additional error may result.

Exhaustive tests of the Eppley pyrheliometer by the manufacturer were afterwards made; and the results forwarded to the Weather Bureau. Insofar as these tests by the manufacturer were similar to those by the writers, the results agree remarkably well, especially considering that each test was conducted independently of the other. The manufacturer also states that he intends to make additional studies of the action of the pyrheliometer and already has taken steps to improve the instrument. Even with its present defects, and the necessity for the calibration curves that are required for accurate data, the Eppley pyrheliometer meets the Weather Bureau specifications, and is the best adapted instrument available for the purposes of the measurements of radiation on a horizontal surface of the type that are conducted by the Weather Bureau.

The total solar and sky radiation pyrheliometers in use at stations have been calibrated by (1) the manufacturer, (2) the Weather Bureau, and (3) the National Bureau of Standards. Some of the calibrations were direct; others were secondary. Previous investigation by the Weather Bureau had shown that the calibration factor varied with season and altitude of the sun, but data based on a constant calibration factor were considered adequate for most purposes. Plans already had been made, and testing apparatus obtained by the Weather Bureau, to check all total solar and sky radiation in operation at stations; therefore, with the growing need for more accurate data, the present project simplified methods of recalibration and brought out the need for obtaining absolute mean horizontality of the pyrheliometers.

Although figures 1 and 2 indicate that for exact pyrheliometry allowance must be made for angle of incidence, such allowance is tedious and perhaps unwarranted in the case of the normal use of Eppley instruments at the various stations. Instead one could construct a plot of average pyrheliometer factor, for the whole day, as a function of time of year, with perhaps a change of calibration factor once a month. A suitable average value of the instrument constant I, cal./sq. cm.×hr. per unit deflection of the electrical instrument, could be obtained as a weighted mean of the values of I throughout the day, weighted in proportion to the intensity of radiation, as follows:

$$I=\frac{(H_S-H_D)_1I_1+(H_S-H_D)_2I_2 \ldots . I_{63^\circ}[(H_D)_1+(H_D)_2+\ldots .]}{(H_S)_1+(H_S)_2 \ldots .}$$

where H_S is the total radiation during individual hours; H_D is diffuse radiation during individual hours; I_1, I_2, ... are average instrument constants during individual hours; I_{63° is the constant for 63° angle of incidence (average value for radiation from a uniform sky).

The most accurate values of I are obtained when monthly average values of H_S and H_D for the different hours of the day are used. Values substantially as good are obtained much more easily if data for a clear day at the middle of the month are used instead. As a result of this study, the Weather Bureau will furnish monthly calibration constants to the solar radiation stations as soon as practicable.

Although the agreement between the two independent calibrations of instrument No. 434 indicates that figure 2 is substantially correct, the pyrheliometric data reported from Cambridge in the MONTHLY WEATHER REVIEW during the past 2 years are somewhat in error, because the data were reported on the basis of the constant calibration factor supplied with the instrument. Anyone using these data and desiring greater accuracy should correct them by figure 2, (or more simply by the average monthly factors which will soon be available), after subtracting diffuse radiation. Corrections for data at other stations will be published shortly after the completion of the recalibration project.

TABLE 1.—*Calibration of M. I. T. pyrheliometer No. 434 by comparison with Weather Bureau pyrheliometer No. 197, Mar. 2, 1941; both instruments were level (as nearly as known); No. 197 was rotated 180° between readings*

[Position 1 is the original orientation; latitude=42°22′]

Mean solar time	Position	Ratio of potentials No. 434–No. 197	Departure from mean
8:37 a. m.	1	1.302	−0.010
8:51 a. m.	2	1.318	+.006
9:12 a. m.	1	1.306	−.006
9:21 a. m.	2	1.330	+.018
9:33 a. m.	1	1.299	−.013
9:44 a. m.	2	1.325	+.013
10:05 a. m.	1	1.308	−.004
10:15 a. m.	2	1.329	+.017
10:56 a. m.	1	1.313	+.001
11:06 a. m.	2	1.312	.000
11:33 a. m.	1	1.302	−.010
11:43 a. m.	2	1.313	+.001
12:00 m.	1	1.309	−.003
12:12 p. m.	2	1.319	+.007
12:48 p. m.	1	1.313	+.001
12:57 p. m.	2	1.306	−.006
1:40 p. m.	1	1.300	−.012
1:50 p. m.	2	1.313	+.001
2:55 a. m.	1	1.301	−.011
3:07 p. m.	2	1.298	−.014
3:42 p. m.	1	1.317	+.005
3:56 p. m.	2	1.320	+.008
Mean ratio			1.312
Average departure from mean			.0076
Average percentage departure			.58